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Technical Report 32

DYNAMIC RESPONSE OF PRESSURE MEASURING SYSTEMS

by

M.F. Lee

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DYNAMIC RESPONSE OF PRESSURE MEASURING SYSTEMS

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SUMMARY

The measurement of time varying pressures is limited when a pressure transmission line must be used. The type of pressure transducer can further limit the speed at which pressure changes can be observed. This report investigates these limitations by subjecting commonly used pressure line tubing and pressure transducers to a step pressure input. By spectrally analysing the response to this step input a frequency response for the system can be determined.

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TABLE OF CONTENTS

Page Nos.

Notation

a	Speed of Sound in Air
J_n	Bessel Function of the First Kind, Order n
L	Length of Tubing
P	Gauge Pressure
R	Radius of Tubing
s	Shear Wave Number
t	Time
V	Volume of Terminal Cavity
x	Axial Distance Along the Pressure Line
γ	Ratio of Specific Heats for Air
μ	Kinematic Viscosity
ω	Angular Frequency
ρ	Density of Air
σ	Prandtl Number

1. Introduction

In order to facilitate the study of transient effects in engine performance, an understanding of the dynamic response of current pressure measurement systems is required. The objective of this study is to gain an appreciation of the limitations that are inherent in any given system used for recording pressures. In general, there are two factors that limit the dynamic response of pressure measurement systems, the response of the pressure transducer and the response of the pneumatic line used to connect the transducer to the pressure source. Incorporated in the latter is the effect of cavities at the ends of the line or discontinuities along the length of the line. Although the response of a pressure transducer cannot be altered it is possible to design pressure lines to optimize the overall system performance.

Several studies have already been conducted to determine line response to various pressure signals. In reference [1] Bergh and Tijdeman have examined the dynamic response of pressure lines to small amplitude, sinusoidally oscillating pressures. Schuder and Binder in reference [2] examine the response of long pressure lines, up to 100 feet, to step pressure inputs. Chapin, reference [5], investigates the response of a multichannel pressure measurement system to a sinusoidal pressure signal.

In this study a step signal is measured using various configurations of pressure line and transducer. The dynamic response is determined by comparing the source pressure signal and the measured signal in the spectral domain. In this way a frequency response for the measurement system is determined.

2. Apparatus and Experimental Method

The step pressure signal for use in this experiment was generated by pressurising a chamber which had an orifice set into the roof. A pressure line or pressure transducer was attached at this point to observe the pressure. The orifice was closed off from the chamber by means of a sealing plate and then vented to atmospheric pressure. The pressure in the chamber held the plate in place against the roof. A dropped weight was used to remove the plate impulsively and thus expose the orifice to the pressure within the chamber. A schematic of the device is shown in figure 1.

To measure the response of different pressure lines, various lengths and diameters of plastic and steel tubing were used to connect the orifice with a CEC 4-316 strain gauge pressure transducer. The natural frequency of this type of transducer is an order of magnitude higher than the frequency range of interest in this experiment. The high frequency ringing that appeared on the output signal, caused by resonance of the transducer at its natural frequency, was removed using a high pass filter. The filter was observed to have negligible effect on frequency response in the 1.0 Hz to 1.0 kHz band. The instrument specifications for the CEC 4-316 transducer indicate that it has a flat response for frequencies up to 10 kHz. Consequently, any difference between the source pressure signal and the measured signal for frequencies less than 1.0 kHz

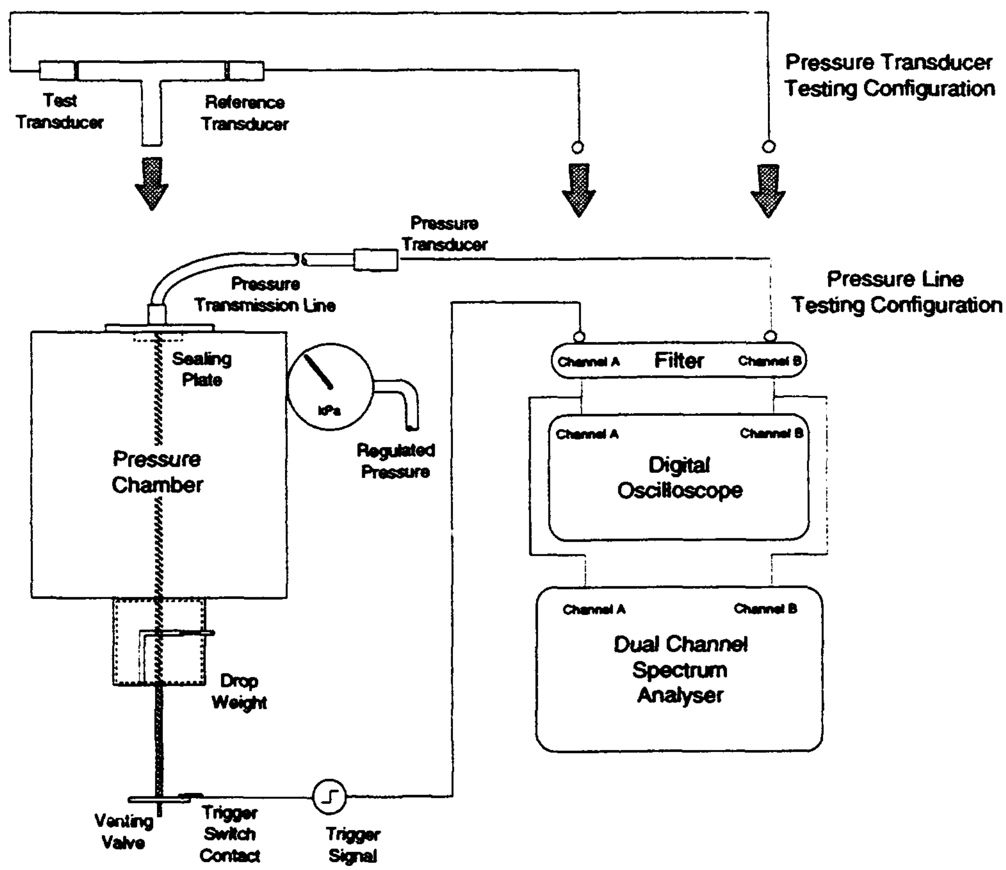


Figure 1: Schematic diagram of the experimental apparatus.

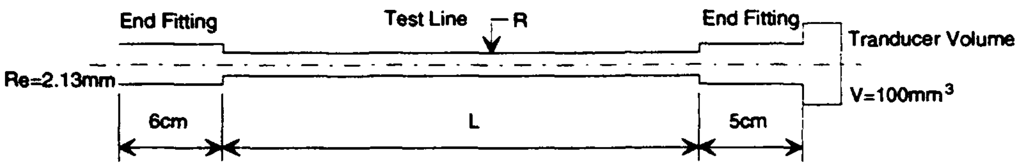


Figure 2: Schematic diagram of the pressure transmission line.

can be attributed to the response of the pressure line between the transducer and the pressure source.

The transient signal from the transducer was viewed using a storage oscilloscope. Simultaneously, the signal was viewed in the frequency or spectral domain using a dual channel spectrum analyser. To synchronise the measurement equipment a triggering signal was generated using a solid state switch actuated by the falling weight. This triggering step signal was also used as the reference signal for determining the transmission response of the lines tested. The transmission response of the line was determined by calculating the transfer function between the spectrum of the measured pressure signal and the spectrum of the reference signal. A short but unspecified time delay existed between the contact of the drop weight on the triggering switch and the exposure of the aperture to the chamber pressure. This was due to the finite time required to transfer the momentum of the drop weight into a force sufficiently large to remove the sealing plate. To compensate for this, a 0.7 msec delay was imposed on the reference signal.

The fittings that were used to connect the pressure line to the step pressure source formed a conduit 60mm long and 4.2 mm in diameter. Similarly, the fittings that connected the pressure transducer to the pressure line formed a conduit 50mm long with the same diameter, terminating in a small volume of approximately 100 mm^3. Figure 2 gives a schematic representation of the test line configuration. The types of transmission lines used are listed in table 1.

The actual pressure signal generated was measured by mounting a piezo-electric transducer flush with the roof of the chamber in place of the pressure transmission line connection. The pressure was found to have a rise time of approximately 0.01 msec. For the purposes of this experiment signal frequency components greater than 1 kHz are not of interest. Thus this rise time, which corresponds to frequency components of order 100 kHz, can be considered to be effectively instantaneous.

Various lengths of each line were tested using a 250 kPa step up from atmospheric pressure. A large pressure step was required to provide adequate signal strength for the higher frequencies. In addition, a 0.8 m length of 2.27 mm ID nylon tubing was subjected to differing sizes of pressure step from 75 kPa up to 250 kPa.

To measure the response of the various models of pressure transducer the pressure

Tube Type	Inside Diameter
Stainless Steel Hypodermic Tubing	1.17mm
Nylon Tubing	2.27mm
Nylon Tubing	4.26mm

Table 1: Pressure Lines Tested

Make	Model	Type	Range
Rosemount	1332	Gauge	0-30 psi
Rosemount	1332	Gauge	0-50 psi
Rosemount	1332	Gauge	0-150 psi
Druck	PDCR 130	Gauge	0-1bar
Druck	PDCR 120/35 WLC	Differential	±50 psi
Setra	239	Differential	±50 psi
Setra	204	Gauge	0-1000 psi
CEC	4-316	Differential	±50 psi

Table 2: Pressure Transducers Tested

signal was split by attaching a T-piece fitting as indicated in figure 1. The test transducer was fitted to one side of the T-piece while a reference transducer was fitted to the opposite side. The configuration was sufficiently symmetric to permit comparison of the signals up to a frequency of 300 Hz. Differences in the geometry of the transducer's end fittings prevented the comparison of higher signal frequencies . A CEC 316 strain gauge transducer was again used to generate the reference signal. Table 2 lists the various models of pressure transducer that were tested.

3. Signal Processing

The spectral transform of a signal is obtained by taking the Fourier transform of the signal in the time domain or real space. By taking the spectral transform of the input pressure signal and the measured pressure signal the frequency response function of the pressure measurement system can be determined. This response function is typically a complex function of frequency, having both real and imaginary parts. Such a function can alternatively be expressed as two separate components, typically. the magnitude and the phase response functions.

The magnitude response gives the amplification of a each frequency component. Thus, if a sinusoidally oscillating signal of some given frequency was measured, the output signal would be amplified by the magnitude response of that given frequency. In addition to this amplification, the signal may lag the measured signal. The measure of this lag is the phase response. The phase angle indicates the fraction of a period that the measured signal leads or lags the actual signal. A negative phase angle indicates

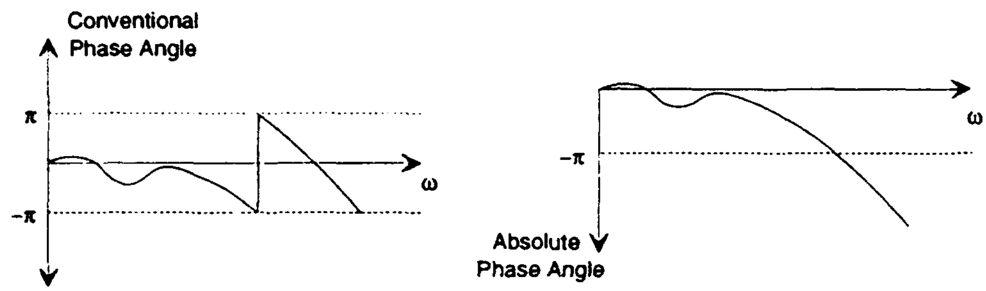


Figure 3: Absolute phase angle has an unrestricted range while the conventional phase angle is restricted to the range $(-\pi, \pi]$.

that the measured signal lags the actual signal while a positive phase angle indicates that the measured angle leads the actual signal. While it is not physically possible for the measured signal to lead the actual signal, the concept of a positive phase angle is sometimes useful in describing the response to periodic signals. If the measured signal lags the actual signal by more than half a period then it can give the appearance of leading the actual signal.

In this report the phase response is presented simply as a time lag for each frequency component. The time lag of a given frequency component is given by dividing the 'absolute' phase angle (see figure 3) by that frequency.

4. Theory

A study by Bergh and Tidjeman, reference [1], gives a closed form solution for the transmission of sinusoidally oscillating pressures in tubing. The line pressure transmission response is defined by the ratio of the transmitted pressure, P_t, to the source pressure, P_s. Consider a pressure source oscillating relative to some ambient pressure with a given amplitude, P_o, and frequency, ω,

$$P_s = P_o e^{i\omega t}$$

the line pressure transmission response has the form,

$$\frac{P_t}{P_s} = Ae^{\phi x} + Be^{-\phi x}$$

The coefficients A and B are chosen to satisfy a given set of boundary conditions and ϕ is given by,

$$\phi = \frac{\omega}{a}\sqrt{\gamma\kappa\frac{J_0(i^{3/2}s)}{J_2(i^{3/2}s)}}$$

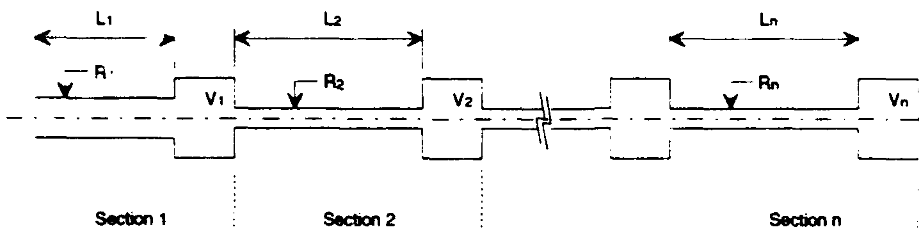


Figure 4: Generalised pressure transmission line schematic.

where,

$$\kappa = 1 + \frac{\gamma - 1}{\gamma} \frac{J_2(i^{3/2}\sigma^{1/2}s)}{J_0(i^{3/2}\sigma^{1/2}s)}$$

and,

$$s = R\sqrt{\frac{\rho\omega}{\mu}}$$

This equation is an approximate solution of the time-dependent Navier-Stokes equations subject to the following conditions:

- the sinusoidal signal is small relative to the mean pressure;
- the internal radius of the tube is small relative to the length of the tube;
- the flow is laminar throughout the system; and
- expansions occur isentropically.

Since in this study the pressure disturbances generated are not small relative to the ambient pressure it is not expected that good agreement will be found with this theory. However, it should serve as a limiting case for comparison.

In reference [4] a response equation is derived from the general solution for a series of connected tubes and volumes, as shown in figure 4. Using the notation presented in this figure the response of the j^{th} section of the transmission line is given by,

$$\begin{aligned}\frac{P_{j-1}}{P_j} &= \cosh(\phi_j L_j) \\ &\quad + \frac{V_j}{\gamma \pi R_j^2} \frac{\phi_j}{\kappa_j} \sinh(\phi_j L_j) \\ &\quad + \frac{R_{j+1}^2}{R_j^2} \frac{\phi_j}{\phi_{j+1}} \frac{\kappa_{j+1}}{\kappa_j} \frac{\sinh(\phi_j L_j)}{\sinh(\phi_{j+1} L_{j+1})} \left[\cosh(\phi_{j+1} L_{j+1}) - \frac{P_{j+1}}{P_j}\right]\end{aligned}$$

The response of the last section is given by,

$$\frac{P_{n-1}}{P_n} = \cosh(\phi_n L_n) + \frac{V_n}{\gamma\, \pi R_n^2} \frac{\phi_n}{\kappa_n} \sinh(\phi_n L_n)$$

Thus the total response is given by the product of the response of each individual line section.

The frequency response for a pressure wave transmitted along a uniform length of line is a function of two parameters, the shear wave number, s, and the non-dimensional frequency, ω/ω_o, where ω is the frequency of pressure oscillation and ω_o is the natural frequency given by,

$$\omega_o = \frac{2\pi}{4} \frac{a}{L} \text{ radians/second}$$

Figure 5 shows the response predicted by this theory for the three types of line tested in this experiment. Note that the resonant values of non-dimensional frequency approach the odd integer values as inside radius increases. This is expected since these resonant frequencies correspond to the closed organ pipe resonance modes. The delay time is non-dimensionalised by a characteristic time, t_o, given by,

$$t_o = \frac{L}{a}$$

In the limiting case of infinite frequency, a non-dimensional time delay of unity would be expected.

5. Results

Figures 6, 7 and 8 show the dimensionless response functions for various lengths of the 1.17mm, 2.27mm and 4.26mm inside diameter pressure transmission lines, respectively. From these results, two points are immediately obvious.

- Firstly, in all cases, a degradation in response is observed between the measurements and that predicted by the above theory. That is, the magnitude response is smaller than that predicted and the delay time is greater than predicted. As mentioned previously, this is expected since the size of the pressure signal is large in comparison to the ambient pressure. This means there is an appreciable flow of air down the pressure line as the pressure step is transmitted. The increase in internal flow increases the viscous interaction between the fluid and the inside wall of the tube, an effect which is similar to reducing inside radius of the tube. Thus increasing the amplitude of a pressure signal will reduce the effective bore radius of the line. This effect was observed in reference [1] where the experimentally determined response of a transmission line consistently corresponds to that predicted for a line of slightly smaller inside radius.

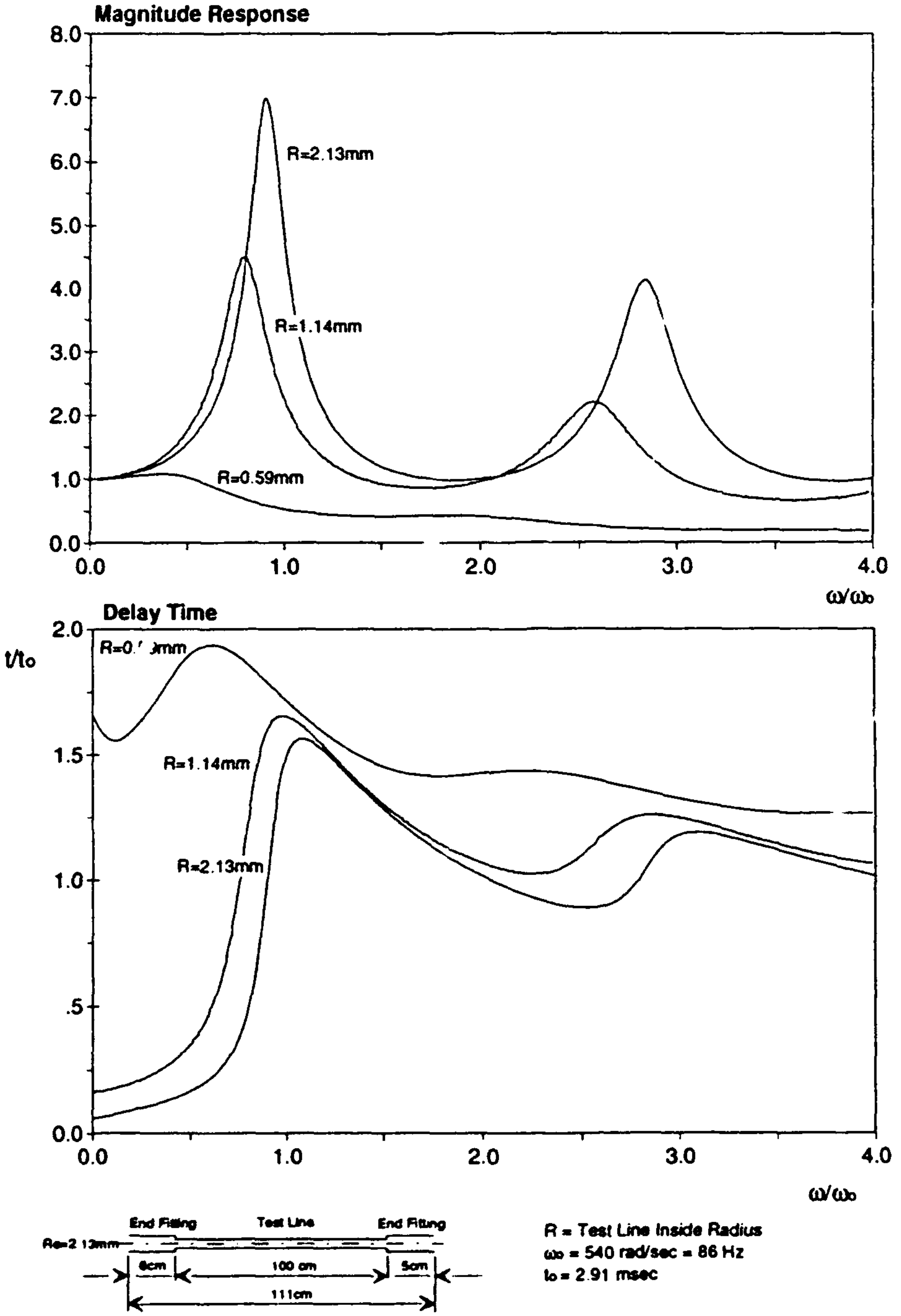


Figure 5: Theoretical prediction of pressure line response.

Bore Radius	Length	Low Pressure Attenuation		High Pressure Attenuation	
		25 Hz	50 Hz	25 Hz	50 Hz
0.59mm	0.32m	1.0	1.1	0.94	0.74
	0.67m	1.1	1.1	0.92	0.26
1.14mm	0.54m	1.1	1.3	1.02	1.05
	0.84m	1.2	2.1	0.94	0.79
2.13mm	0.38m	1.15	1.55	1.05	1.12
	0.73m	1.05	1.10	1.10	1.15

Table 3: Attenuation of a 50 Hz pressure signal. High and low pressure responses give an indication of the change in response from the ideal low pressure response predicted by the theory presented and that measured experimentally from a 250 kPa pressure step.

- Secondly, the theory predicts that the non-dimensional response function is independent of the length of the transmission line. This is clearly not observed in this experiment. Instead the response is attenuated as length increases, consistent with an increase in the viscous effect and leading to a reduction of the effective bore radius. The response of the shorter line lengths in figure 8 seems to indicate that the response will tend towards the predicted response as viscous effects become less prevalent.

The response of the narrowest bore tubing appears to contradict the trend observed for the larger bore tubing. The dimensionless response appears to improve with increasing tube length. The reason for the observed trend is due to the large discontinuity between the bore of the tubing and that of the end fittings. These discontinuities impede the pressure signal as it enters and leaves the fine bore tubing. As the tubing length decreases this discontinuity becomes relatively more significant and consequently, the non-dimensional response is degraded.

The effect of increasing the pressure signal amplitude can be seen from the results shown in figure 9. Increasing pressure degrades the magnitude response and increases the time delay. Table 3 gives the attenuation at 25 and 50 Hz of a number of line lengths and bore radii.

From the tests performed on pressure transducers it was found that all models not equipped with internal amplifiers exhibited a flat response over the measured frequency range (0-400 Hz). However, the Rosemount 1332 and Druck PDCR 130 models, which have internal signal amplifiers, did show a fall off in response with increasing frequency. Figure 10 shows the magnitude response for these transducers. A uniform 1.0 millisecond delay was observed in all of the Rosemount models, while no such delay was observed in the Druck model.

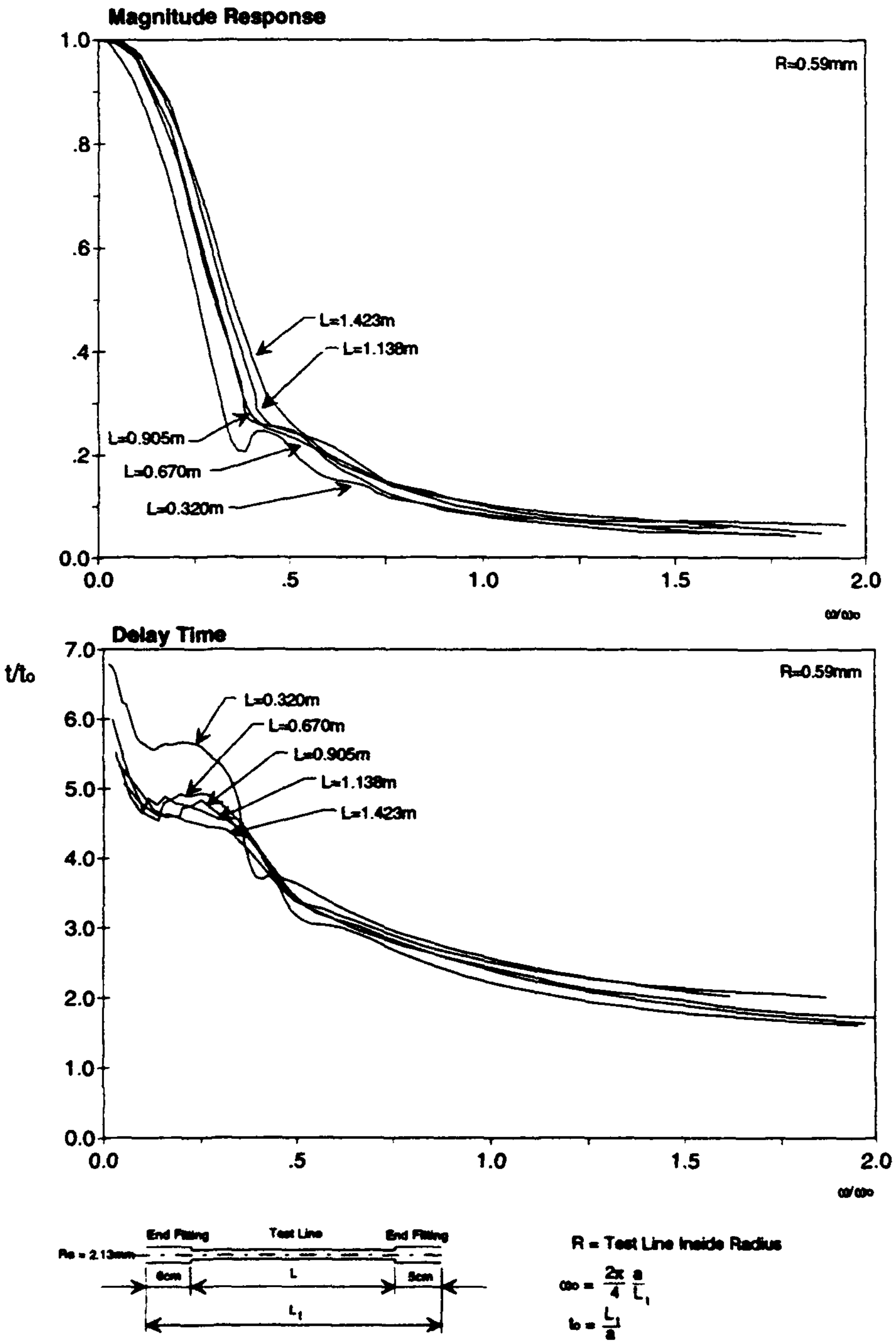


Figure 6: Response of 1.17mm I.D. pressure line.

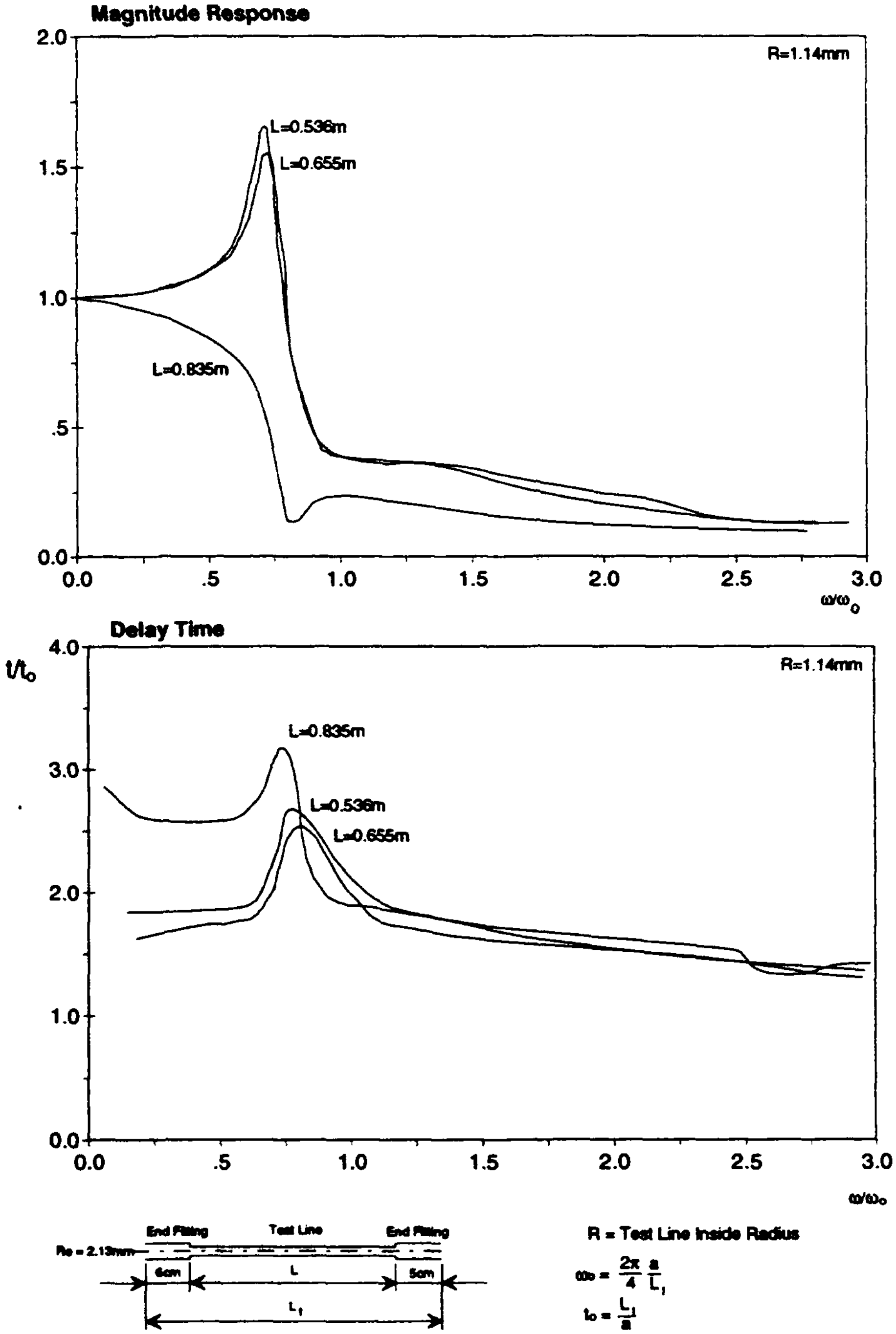
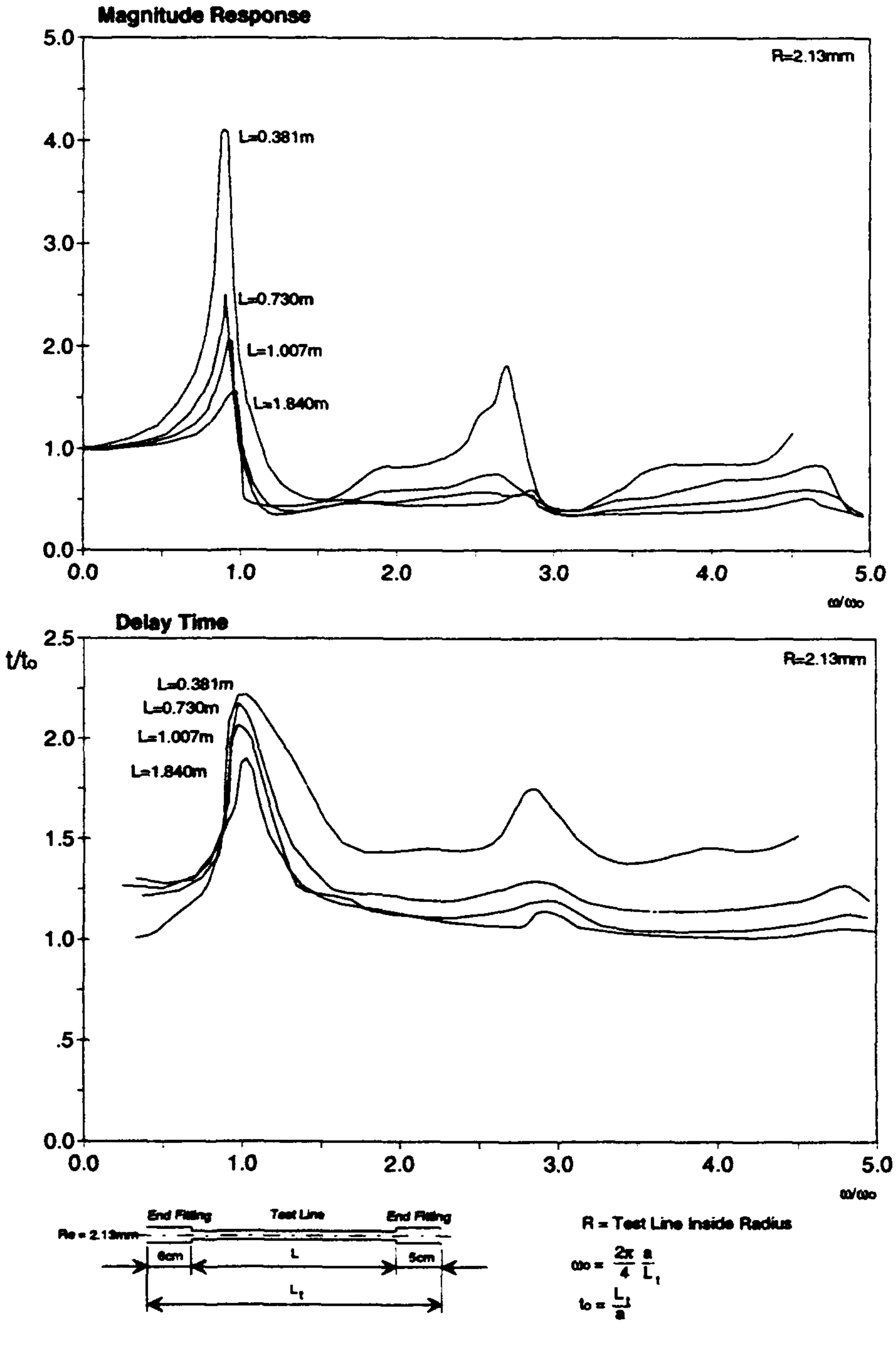


Figure 7: Response of 2.27mm I.D. pressure line.



$$\omega_o = \frac{2\pi}{4}\frac{a}{L_t}$$

$$t_o = \frac{L_t}{a}$$

Figure 8: Response of 4.26mm I.D. pressure line.

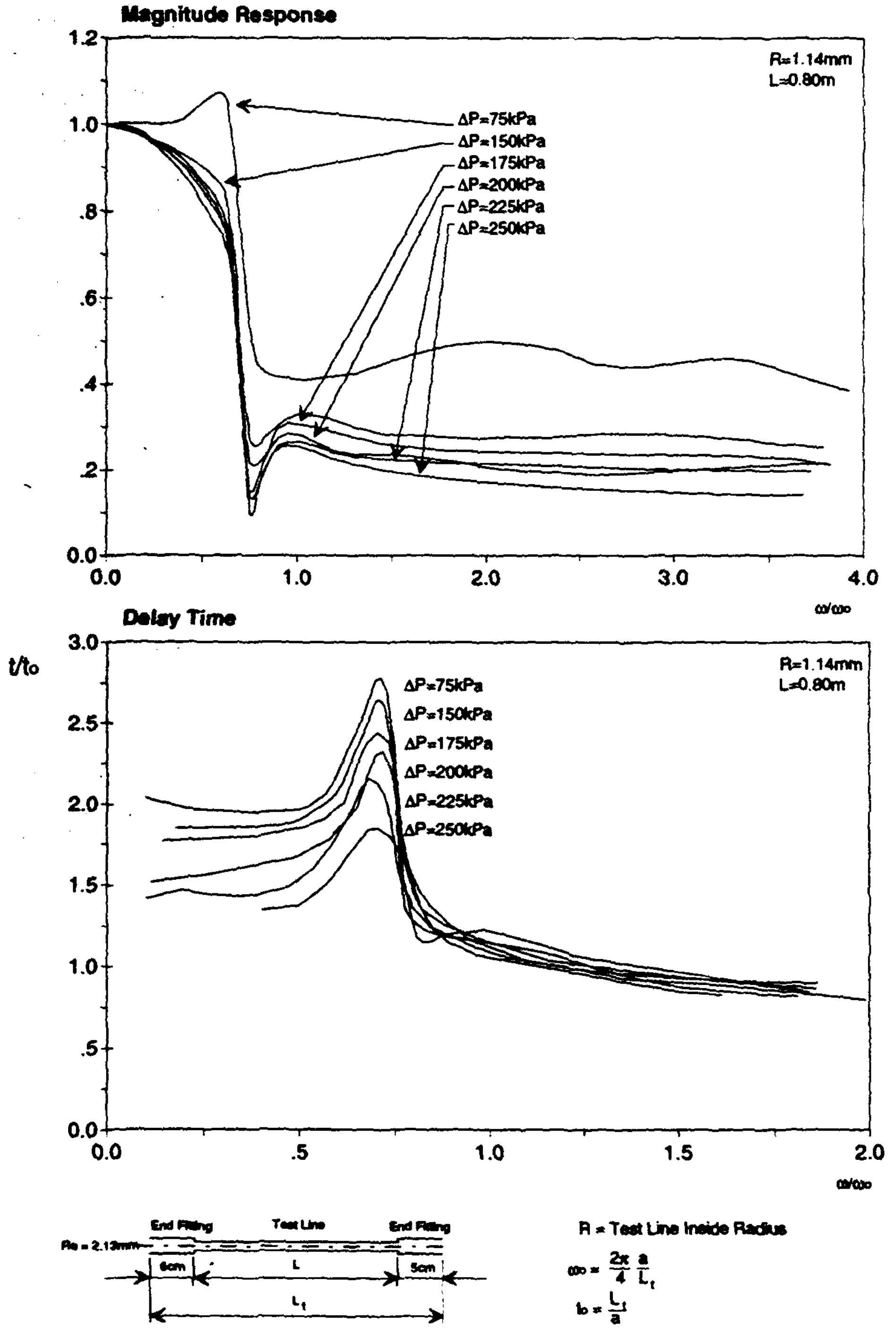


Figure 9: Variation in response with increasing pressure step.

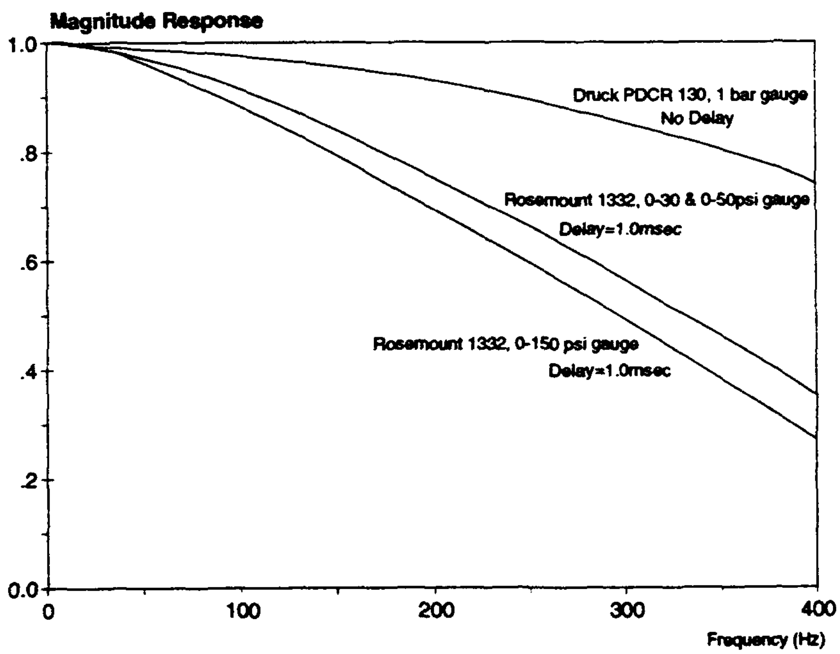


Figure 10: Response of internally amplified models of pressure transducer.

6. Conclusions

From this study the following conclusions are made:

1. The capacity of a pressure line to transmit high frequency signals is reduced as the bore radius is reduced. That is, the amplitude response decreases and the delay between the actual pressure signal and the measured pressure signal is increased.

2. As the bore radius of the transmission line is increased the level of distortion in the frequency response increases. This is due to decreased viscous damping of the resonant modes within the transmission line.

3. For small pressure signals, where the air flow associated with the pressure transmission is insignificant, the non-dimensional response function is independent of transmission line length. The frequency response in this case is still affected by line length since the characteristic frequency, ω_o, is inversely proportional to length.

4. For large pressure signals, where a significant flow of air along the transmission line occurs, the non-dimensional response is reduced with increasing transmission line length.

5. As the amplitude of the pressure signal increases the response of a given transmission line is decreased.

6. In general, pressure transducers without an internal signal amplifier have a 'flat' frequency response up to at least 400 Hz and in most cases up to 10 kHz.

7. All of the self amplified type pressure transducers tested exhibit a frequency response which falls off with increasing frequency and are ineffective when measuring signal frequencies above 1 kHz. The observed fall off in response is caused by the electrical impedance internal to these transducers.

When measuring dynamic pressures it is recommended that the pressure transmission line used has a natural frequency well above that of any frequency component likely to be encountered. This consideration will specify the maximum length of transmission line that can be used. The size of line chosen will be governed by the degree of distortion or attenuation that is tolerable.

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